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Revealing of silhouette of an exoplanet from its transit light-curve

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Abstract

A new method for reconstruction of silhouette of a transiting exoplanet is developed on the basis of derivative analysis of the transit light-curve (TLC). The method is able to detect the non-circular shapes of exoplanetary shadows, although sometimes the reconstructed non-spherical silhouettes are distorted. The proposed method shows the presence of a ring or disk for the planet KOI 1729.01, whereas other similarly studied objects (13 from 18) have quasi-circular shadows.

1. Introduction

Traditionally, the shape of transiting exoplanets was supposed to be a circle ([1] and therein). However, exorings, oblateness as well as circumplanetary dust can distort the silhouette of planet. Although there are inconclusive searches ([2] and therein) for exo-rings, they remain non-effectively, being focused on second-order photometrical differences between the fitted ringed and ring-less transiter models. Moreover, a ring-less model can produce practically the same TLC, as the ringed one does, but special fitting of impact parameter b and semi-major axis a of orbit would be needed. The generic shadow imaging of a transiting object from its TLC, without an a-priori assumption on its phenomenology, has difficulties with the degeneracies, low resolution, artifacts and selectivity to geometry [3]. In view of these complications, we propose a special method for the probing of non-spherical exoplanetary silhouettes.

2. Method

We use publically available *Kepler* short-cadence light-curves [4] after Pre-search Data Conditioning. After an iterative exclusion of outliers and data whitening, we obtain the TLC flux decrease during individual transits $\Delta F(\Delta t)$ (Fig. 1a), used in further analysis [3]. Here Δt is the time counted from the mid-time of the transit, calculated using cumulative transit parameters (reference time, period, and duration) in [4]. The proposed method analyses behaviour of the derivative $\partial(\Delta F)/\partial(\Delta t)$ during ingress/egress (Fig. 1b), which depicts the space distribution of the obscuring matter. The main problem here is the transformation of Δt and $\partial(\Delta F)/\partial(\Delta t)\equiv D$, to the orthogonal space coordinates X and Y, respectively. Taking X-axis directed from the planetary centre to the nearest point of stellar limb, one can relate them to the planetary radius R_p, from [4] as follows:

$$X = (\Delta t — \Delta t_{max})/T_R \quad (1)$$

$$Y = |D|/D_R \quad (2)$$

where Δt_{max} is the time of maximal $|D|$; T_R is defined for the spherical transiter with radius R_p, as the time during which the centre of assumed circular shadow reaches the limb of stellar disk. Taking the area of the shadow πR_p^2 to be the same, independently of the transiter's shape, one can write $2(|X_1|+|X_2|)<Y>=\pi$, were $|X_1|$ and $|X_2|$ are the maximal absolute values of X at the *observed* start (Δt_{start}) and end (Δt_{end}) times of the transit, respectively. The derivative of the ingress and egress parts is averaged over $\Delta t_{start}<\Delta t<\Delta t_{max}$ and $\Delta t_{max}<\Delta t<\Delta t_{end}$, respectively, so that $<Y>=<|D|>/D_R$. Therefore, using Eq. (2), one can obtain

$$D_R = 2(|X_1|+|X_2|)<|D|>/\pi \quad (3)$$

For a circular shadow, the timescale T_R can be found using the transit cumulative TLC parameters from [4]:

$$T_R = 0.5KP_{tr}(\varphi_1 — \varphi_2)/\pi \quad (4)$$

where φ_1 = arctg (Δ_1/r) and φ_2 = arctg (Δ_2/r). Here $\Delta_1 = [(R_s + R_p)^2 - (bR_s)^2]^{1/2}$, $\Delta_2 = [R_s^2 - (bR_s)^2]^{1/2}$, $r = [a^2 - (bR_s)^2]^{1/2}$, and R_s is the stellar radius. To correct the slight shift of Δt_{max} due to limb darkening, the factor K=$(|X_1|+|X_2|)/2$= (1.12 … 1.31) is added in Eq. (4). This factor is calculated using synthetic TLC for a circular exoplanet with radius R_p and the best limb darkening approximation from [5] for the given system parameters from [4]. For the best resolution of derivative *D*, we use the phase-folded TLC over the whole light-curve. Since the method cannot distinguish between positive and negative *Y*, we consider in silhouette reconstructions both variants.

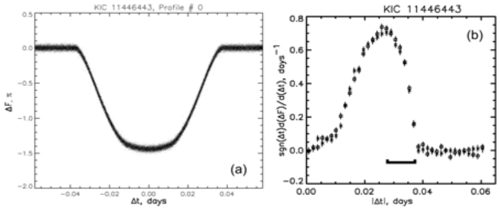

Figure 1: Sample case of KOI 1.01: **(a)** the folded TLC and **(b)** its derivative for ingress (squares) and egress (crosses) parts. The bold bar marks the analyzed part of the derivative.

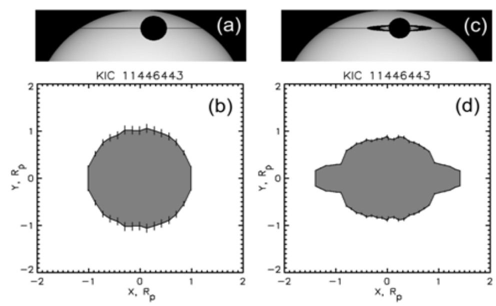

Figure 2: **(a)** published [4] transit geometry and **(b)** the corresponding silhouette reconstruction using the derivative from Fig. 1b; **(c)** transiter's model with an imposed ring (total obscured area is the same as in (a)) and **(d)** its disturbed silhouette reconstructed from the corresponding synthetic TLC.

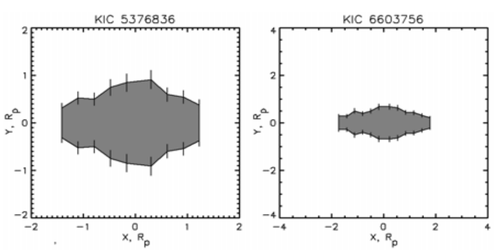

Figure 3: Elongated silhouettes, reconstructed for the TLCs of KOI 182.01 (left) and KOI 1729.01 (right).

3. Results

Figure 2 demonstrates the reconstruction capability of the method in the cases of real TLC of confirmed exoplanet (Fig.2a,b) and a simulated transit with an imposed ring (Fig.2c,d). In both cases the transiter's silhouette is successfully revealed. In the case of imposed ring, the reconstructed silhouette resembles the input geometry of the transiting matter with some distortions due to inclined stellar limb. Fig.3 shows the silhouettes obtained for the real TLCs of K0I 182.01 and 1729.01. Both cases were identified as false-positive stellar-eclipses in [4]. However, their small impact parameters and planetary size exclude partial eclipses. Since the values *a* and *b* from [4], fitted in accordance with celestial mechanics [1], were used, the silhouette elongation cannot be removed (at least for KOI 1729.01) by simple re-fitting of transit parameters. Additionally, the TLCs of 16 KOI objects from the list in [2] with signal-noise ratio *S/N*>1500 were processed. Practically all selections show quasi-circular silhouettes like in Fig.2b, except of problematic KOI 13.01 (incorrect LC preparation) and KOI 6016.01 (partial eclipse).

4. Summary and Conclusions

The proposed method can indicate non-circular shape of exoplanetary shadows. In particular, KOI 1729.01 shows the presence of a ring or disk. However, the reconstructed transiter's silhouette could be distorted.

Acknowledgements

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